

Non-thermal Emissions from Cool Cores Heated by Cosmic-Rays in Galaxy Clusters

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ABSTRACT

We study non-thermal emissions from cool cores in galaxy clusters. We adopted a recent model, in which cosmic-rays (CRs) prevail in the cores and stably heat them through CR streaming. The non-thermal emissions come from the interaction between CR protons and intracluster medium (ICM). Comparison between the theoretical predictions and radio observations shows that the overall CR spectra must be steep, and most of the CRs in the cores are low-energy CRs. Assuming that the CRs are injected through AGN activities, we study the nature of the shocks that are responsible for the CR acceleration. The steep CR spectra are likely to reflect the fact that the shocks travel in hot ICM with fairly small Mach numbers. We also study the dependence on the CR streaming velocity. The results indicate that synchrotron emissions from secondary electrons should be observed as radio mini-halos in the cores. In particular, low-frequency observations (e.g. *LOFAR*) are promising. On the other hand, the steepness of the spectra makes it difficult to detect non-thermal X-ray and gamma-ray emissions from the cores. The low-energy CRs may be heating optical filaments observed in the cores.

Subject headings: cosmic rays — galaxies: clusters: general — galaxies: clusters: intracluster medium — radiation mechanisms: nonthermal

1. Introduction

Clusters of galaxies are filled with hot X-ray gas or intracluster medium (ICM) with temperatures of $\sim 2\text{--}10$ keV. While the radiative cooling time of the ICM is longer than the age of the Universe in most of the region in a cluster, the exception is the core, which is $r \lesssim 100$ kpc from the cluster center. If there is no heating source, the ICM in the core cools and a flow toward the cluster center should develop (a cooling flow). However, X-ray observations have denied the existence of massive cooling flows in clusters, which suggests that the cores should be heated by some unknown sources (e.g. Ikebe et al. 1997; Makishima et al. 2001; Peterson et al. 2001; Tamura et al. 2001; Kaastra et al. 2001; Matsushita et al. 2002). Since active galactic nuclei (AGNs) are often found in the cores, they are often thought to be the heating sources (e.g. Churazov et al. 2001; Quilis, Bower, & Balogh 2001; Brüggen & Kaiser 2002; Basson & Alexander 2003). X-ray observations have actually revealed the interaction between AGNs and the ambient ICM (e.g. Fabian et al. 2000; McNamara et al. 2000; Blanton et al. 2001; McNamara et al. 2001; Mazzotta et al. 2002; Fujita et al. 2002; Johnstone et al. 2002; Kempner, Sarazin, & Ricker 2002; Takizawa et al. 2003; Fujita et al. 2004b). However, even if AGNs can produce enough energy to heat the core, the energy must deliberately be transported to the surrounding ICM in the core. For example, conventional mechanical heating such as the dissipation of weak shocks and sound waves often cause thermal instabilities (Fujita & Suzuki 2005; Mathews, Faltenbacher, & Brighenti 2006). Therefore, turbulence may essentially be required to hold the instabilities for such heating mechanisms.

Cosmic-rays (CRs) may be another channel of transporting energy to the ICM (e.g. Tucker & Rosner 1983; Rephaeli 1987; Rephaeli & Silk 1995; Colafrancesco, Dar, & De Rújula 2004; Pfrommer et al. 2007; Jubelgas et al. 2008). Especially, CR streaming has been studied as an energy transport mechanism (Rephaeli 1979; Böhringer & Morfill 1988; Loewenstein, Zweibel, & Begelman 1991; Guo & Oh 2008). In this mechanism, CRs streaming in the ICM excites Alfvén waves. The CRs interact and move outwards with the waves. The PdV work done by the CRs effectively heat the ICM. Recently, using numerical simulations, we showed that the CR streaming can stably heat the core for a long time (Fujita & Ohira 2011, hereafter Paper I). The reason of the stability is that the CR pressure is insensitive to changes in the ICM and that the density dependence of the heating term is similar to that of radiative cooling. Moreover, CRs can prevail in the entire core and the heating is not localized around the source. The CRs may be provided in the core not only by AGNs but also through pumping by turbulence (Enßlin et al. 2011).

In this paper, we study the non-thermal emission from the CRs that heat cool cores and the AGN activities that are responsible for the acceleration of the CRs. It is to be noted that non-thermal emissions from CR protons accelerated by AGNs in the cores have been

studied by Fujita et al. (2007). However, they studied CR acceleration associated with a single AGN burst with an extremely large energy, and they did not consider the heating of the ICM by CR streaming. This paper is organized as follows. In § 2, we explain our models on core heating and AGN activities that are responsible for the generation of CRs. In § 3, we present the results of our calculations and compare them with observations. In § 4, we discuss the implications of our results, and § 5 is devoted to conclusions. We refer to protons as CRs unless otherwise mentioned.

2. Models

2.1. Cosmic-Ray Distributions

In Paper I, we studied heating of a cool core by CRs injected through the activities of the central AGN. The CRs travel with Alfvén waves in the ICM. They amplify the waves, which heat the surrounding ICM. In this subsection, we briefly summarize the models to obtain CR and ICM distributions.

For simplicity, we assumed that the cluster is spherically symmetric. The flow equations are

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho u) = 0, \quad (1)$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho u^2) = -\rho \frac{GM(r)}{r^2} - \frac{\partial}{\partial r} (P_g + P_c + P_B), \quad (2)$$

$$\begin{aligned} \frac{\partial e_g}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 u e_g) &= -P_g \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 u) + \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 \kappa(T) \frac{\partial T}{\partial r} \right] \\ &\quad - n_e^2 \Lambda(T) + H_{\text{st}} + H_{\text{coll}}, \end{aligned} \quad (3)$$

$$\frac{\partial e_c}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tilde{u} e_c) = -P_c \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tilde{u}) + \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 D(\rho) \frac{\partial e_c}{\partial r} \right] - \Gamma_{\text{loss}} + \dot{S}_c, \quad (4)$$

where ρ is the gas density, u is the gas velocity, P_g is the gas pressure, P_c is the CR pressure, P_B is the magnetic pressure, G is the gravitational constant, $M(r)$ is the gravitational mass within the radius r , $\kappa(T)$ is the coefficient for thermal conduction and T is the temperature, n_e is the electron density, Λ is the cooling function, H_{st} is the heating by CR streaming, H_{coll} is the heating by Coulomb and hadronic collisions, \tilde{u} is the CR transport velocity, $D(\rho)$ is the diffusion coefficient for CRs averaged over the CR spectrum, Γ_{loss} is the energy loss by Coulomb and hadronic collisions, and \dot{S}_c is the source term of CRs. Energy densities of the gas and the CRs are respectively defined as $e_g = P_g/(\gamma_g - 1)$ and $e_c = P_c/(\gamma_c - 1)$, where $\gamma_g = 5/3$ and $\gamma_c = 4/3$. In this paper, we do not treat models with thermal conduction, and

thus $\kappa = 0$. The terms for radiative cooling Λ , Coulomb collisions H_{coll} , hadronic collisions H_{coll} , diffusion $D(P)$, and the energy loss Γ_{loss} are the same as those in Paper I. The source term of CRs is given by $\dot{S}_c \propto L_{\text{AGN}}$, where L_{AGN} is the energy injection rate from the AGN. We assume that $L_{\text{AGN}} = \epsilon \dot{M} c^2$, where ϵ is the parameter, \dot{M} is the inflow rate of the gas toward the AGN, and c is the speed of light.

The CR transport velocity in equation (4) is given by $\tilde{u} = u + v_A$, where $v_A = B/\sqrt{4\pi\rho}$ is the Alfvén velocity for a magnetic field B , which evolves as $B \propto \rho^{2/3}$. The initial magnetic field at the cluster center is $B_0 = 10 \mu\text{G}$. The wave energy $U_A = \delta B^2/(4\pi)$, where δB is the magnetic field fluctuation, is amplified by the PdV work done by the CRs on Alfvén waves:

$$\frac{\partial U_A}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 U_A \left(\frac{3}{2} u + v_A \right) \right] = u \frac{\partial}{\partial r} \frac{U_A}{2} - v_A \frac{\partial P_c}{\partial r} - H_{\text{st}} \quad (5)$$

(McKenzie & Völk 1982; Böhringer & Morfill 1988). This equation is more correct than that we adopted in Paper I (equation [6] in that paper), because it is based on wave energy conservation. However, the results are not affected by this change of the equation (see § 3). After the wave energy increases to $U_A \sim U_M$, where U_M is the energy of the background magnetic field, the waves are expected to heat ICM through non-linear damping (e.g. Ohira et al. 2009; Gargaté et al. 2010). Thus, we give the heating term for CR streaming by

$$H_{\text{st}} = \Gamma v_A \left| \frac{\partial P_c}{\partial r} \right| \quad (6)$$

(Völk et al. 1984; Kang & Jones 2006). We simply give $\Gamma = U_A/U_M$ for $U_A < U_M$ and $\Gamma = 1$ after U_A reaches U_M .

2.2. Non-Thermal Emissions

Although by solving equations presented in § 2.1 we can obtain the profile of the ICM and that of the CR pressure $P_c(r)$ required to heat the core effectively (Paper I), we do not have information on the energy spectrum of the CRs. Thus, we need to specify the spectrum of the CRs to calculate the non-thermal emissions from the CRs.

We assume that the central AGN drives outgoing shock waves and form cocoons (or bubbles) inside them. In the following, we show a description of their evolution (position, velocity, Mach number as functions of time). The shocks should inject CRs with varying efficiencies and spectra. At some moment this injection will be maximal (actually, this moment differs for different CR energy ranges). We only consider the efficiency and Mach number at this moment and fix these numbers by requesting them to reproduce the observed

radio emission for the sake of simplicity, although there would be a more physical approach to calculate the injection evolution and the full injected CR spectrum, assuming the AGN energy release, timescale, and initial cocoon radius.

The CRs are accumulated in the core through the AGN activities. In Paper I, we studied continuous CR injection as a time average, although the supply of the CRs may be intermittent. Each activity of the AGN is approximated by an instantaneous explosion. Thus, the shock expands in the ICM like a supernova remnant in the Galaxy, and the shock velocity depends on the energy input from the AGN.

In Paper I, we obtained the profiles of the ICM density $\rho(r)$, the temperature $T(r)$, and the magnetic field $B(r)$ at a given time. We approximate the density profile of the ICM by a power-law:

$$\rho_{\text{ICM}}(r) = \rho_{\text{in}}(r/r_{\text{in}})^{-\omega}, \quad (7)$$

where ρ_{in} is the ICM density at the inner boundary ($r_{\text{in}} = 5$ kpc). Using a shell approximation (e.g. Ostriker & McKee 1988), the radius of the shock can be written as

$$R_s = \xi \left(\frac{E_a}{\rho_{\text{in}} r_{\text{in}}^\omega} \right)^{1/(5-\omega)} t_a^{2/(5-\omega)}, \quad (8)$$

where

$$\xi = \left[\left(\frac{5-\omega}{2} \right)^2 \frac{3}{4\pi} \frac{(\gamma_g + 1)^2 (\gamma_g - 1) (3 - \omega)}{9\gamma_g - 3 - \omega(\gamma_g + 1)} \right]^{1/(5-\omega)}, \quad (9)$$

E_a is the energy released by the AGN, and t_a is the time elapsed since the last energy input from the AGN. The velocity of the shock is given by

$$V_s = \frac{dR_s}{dt_a}. \quad (10)$$

The Mach number of the shock is given by $M_s = V_s/c_s(R_s)$, where c_s is the sound velocity. Since we know the profile of the ICM temperature $T(r)$, we can construct the profile of the sound velocity $c_s(r)$. Therefore, if M_s and E_a are given, the shock radius R_s , velocity V_s , and the time t_a that satisfy equations (8) and (10) can be specified.

In reality, the spectrum of accelerated CRs at the shock may change during the expansion of the cocoon. Probably, the spectrum is flat, when the cocoon is young, and the shock velocity and the Mach number are large. Then it gradually steepens as the Mach number decreases, and CR acceleration ceases when the Mach number approaches $M_s \sim 1$. However, we consider a typical Mach number M_{st} around which most CRs are accelerated. In other words, we consider a typical spectrum of CRs that are accelerated when the injection of CRs becomes maximal. We treat M_{st} and E_a as parameters. The shock radius, velocity, and age

when $M_s = M_{st}$ are $R_s = R_{st}$, $V_s = V_{st}$, and $t_a = t_{at}$, respectively. We also assume that the spectrum of CRs that are just accelerated at $r \sim R_{st}$ has a form of

$$N(p, r) \propto p^{-x} e^{-p/p_{\max}}, \quad (11)$$

where p is the CR momentum, x is the index, and p_{\max} is the cutoff momentum of the CRs. Since we already know CR pressure $P_c(r)$, the normalization of relation (11) is determined by the relation

$$P_c(r) = \frac{c}{3} \int_{p_{\min}}^{\infty} \frac{p^2 N(p, r)}{\sqrt{p^2 + m^2 c^2}} dp, \quad (12)$$

where m is the proton mass.

The index is given by $x = (r_b + 2)/(r_b - 1)$, where r_b is the compression ratio of the shock (Blandford & Eichler 1987), which is given by

$$r_b = \frac{(\gamma_g + 1)M_{st}^2}{(\gamma_g - 1)M_{st}^2 + 1}. \quad (13)$$

Since the cooling of CR protons is not effective, the maximum energy of protons corresponding to p_{\max} is determined by the age of the shock and is represented by

$$E_{\max} \sim 1.6 \times 10^4 \left(\frac{V_{st}}{10^3 \text{ km s}^{-1}} \right)^2 \left(\frac{B_d}{10 \mu \text{ G}} \right) \left(\frac{t_{at}}{10^7 \text{ yr}} \right) \text{ TeV}, \quad (14)$$

where B_d is the downstream magnetic field at $r = R_{st}$ and is given by $B_d = r_b B$ (Yamazaki et al. 2006; Fujita et al. 2007). That is, the background magnetic field B is amplified by the compression ratio r_b (equation [13]). Although some particles may be accelerated to higher energies when the expansion velocity of the cocoon was larger, their contribution to the overall spectrum is expected to be small.

The CRs injected at $r \sim R_{st}$ propagate in the ICM with Alfvén waves. Although adiabatic cooling may change E_{\max} , it does not change the index x in relation (11). Moreover, the results in § 3 show that the CR spectra must be steep. Thus, the results are not sensitive to the value of E_{\max} . Therefore, we do not consider the adiabatic cooling for E_{\max} and adopt the relations (11) and (12) at any radius r , although the adiabatic cooling was considered when we calculated P_c in Paper I. Since we expect that thermal protons with higher energies are accelerated as CRs, we assume that the minimum momentum of the CRs is $p_{\min} = 4mc_{sd}$, where c_{sd} is the sound velocity of the ICM at the downstream of the shock at $r = R_{st}$, which is obtained from the Rankine-Hugoniot relations for given $c_s(R_{st})$ and M_{st} :

$$c_{sd} = c_s \frac{\sqrt{2\gamma_g M_{st}^2 - (\gamma_g - 1)} \sqrt{(\gamma_g - 1)M_{st}^2 + 2}}{(\gamma_g + 1)M_{st}}. \quad (15)$$

In this way we have the CR spectrum at each radius for given M_{st} and E_a .

For a given CR proton spectrum, we calculate radiation from them. Non-thermal emission originated from CR protons in the central region of clusters have been studied by several groups (e.g. Miniati 2003; Pfrommer & Enßlin 2004; Keshet & Loeb 2010). In this paper, we adopt the model of Fujita et al. (2009), in which they calculated non-thermal emissions from supernova remnants. We consider the synchrotron, bremsstrahlung, and inverse Compton (IC) emissions from secondary electrons created through the decay of charged pions that are generated through proton-proton collisions. IC emissions are created by electrons that scatter Cosmic Microwave Background (CMB) photons. We also consider π^0 -decay gamma-rays through proton-proton collisions. We do not consider emissions from primary electrons that are directly accelerated at the shock, because we did not calculate the distribution of the primary electrons in Paper I. Because of the short cooling time of electrons, emissions from primary electrons will disappear soon after their acceleration is finished (Fujita et al. 2007).

The photon spectra are calculated based on the radiation models of Fang & Zhang (2007). For the production of secondary electrons and π^0 -decay gamma-ray photons through proton-proton interactions, we use the code provided by Karlsson & Kamae (2008). The spectrum of the secondary electrons are given by $N_e(E_e) = t_{\text{cool},e}(E_e) Q_e(E_e)$, where E_e is the electron energy, $t_{\text{cool},e}$ is the cooling time of an electron, and Q_e is the production rate of the secondary electrons. For the cooling, we include synchrotron cooling, IC scattering, Bremsstrahlung, and Coulomb loss.

3. Results

Since we replaced the equation for the wave energy U_A (equation [6] in Paper I) with equation (5), we recalculate the distributions of the ICM and CRs and show them in Figures 1 and 2. The cluster is initially isothermal with $P_c = 0$. The input parameters are the same as those of Model LCR0 in Paper I, and we simply refer to this model as LCR0 again. The gravitational potential adopted in this model is that of the Perseus cluster. The efficiency of AGN energy input is $\epsilon = 2.5 \times 10^{-4}$. The results are almost identical to those in Paper I (Figures 2 and 4 in that paper). This is because Γ rapidly approaches one after L_{AGN} increases regardless of the equation we adopted. The ICM temperature outside the core is ~ 7 keV. The heating by CR streaming and the radiative cooling are well-balanced at $t \gtrsim 4$ Gyr.

Figure 3 shows the spectra of a region including the entire core ($r < 1$ Mpc) at $t = 9$ Gyr for Model LCR0. The slope of the ICM density profile is assumed to be $\omega = 1$, which is a good

approximation for $r \lesssim 70$ kpc (Figure 1b). The distance to the cluster is 78.4 Mpc, which is the one for the Perseus cluster. In this figure, we take $M_{st} = 2.1$ and $E_a = 1 \times 10^{60} \text{ erg s}^{-1}$; we first give E_a , and then adjust M_{st} in order to be consistent with radio observations for the mini-halo in the Perseus cluster (Sijbring 1993; Gitti, Brunetti, & Setti 2002). Since the Mach number M_{st} is fairly small, the CR spectrum is steep ($x = 3.2$). The maximum energy of the CRs is $E_{\text{max}} = 1.5 \times 10^5 \text{ TeV}$, the radius and age of the shock are $R_{st} = 22 \text{ kpc}$ and $t_{at} = 6.0 \times 10^6 \text{ yr}$, respectively. The spectrum of thermal Bremsstrahlung is shown for comparison.

The slope of the synchrotron and IC scattering spectra at the higher energy side can be explained by a simple calculation. The slope of the energy spectrum of secondary electrons are the same as that of protons ($x = 3.2$), if radiative cooling is not effective. However, cooling by synchrotron radiation and IC scattering increases the slope by one and it becomes $x' = 4.2$ (e.g. Sarazin 1999). The spectral indices of the synchrotron emission and IC scattering are represented by $\alpha = (x' - 1)/2 = 1.6$ (e.g. Rybicki & Lightman 1979), which is consistent with those in Figure 3 ($f_\nu \propto \nu^{-\alpha}$).

We found that the results for $M_{st} = 2.1$ and $E_a = 1 \times 10^{61} \text{ erg s}^{-1}$ are almost the same as those for $M_{st} = 2.1$ and $E_a = 1 \times 10^{60} \text{ erg s}^{-1}$. In the former case, the shock radius and age are $R_{st} = 59 \text{ kpc}$ and $t_{at} = 1.4 \times 10^7 \text{ yr}$, respectively. Although the maximum energy of the CRs is increased ($E_{\text{max}} = 2.7 \times 10^5 \text{ TeV}$), the steep CR spectrum or the large x obscures the effect. This means that the radiation from the cool core is insensitive to the strength of an AGN activity (E_a) for a *given* $P_c(r)$. Figure 4 shows the spectra when $M_s = 1.8$ and 4.0 for $E_a = 1 \times 10^{60} \text{ erg s}^{-1}$. The indices are $x = 3.8$ and 2.3, respectively. Compared with the results of $M_s = 2.1$ and $E_a = 1 \times 10^{60} \text{ erg s}^{-1}$, the non-thermal emissions are weaker (stronger) when M_s is smaller (larger), and the synchrotron radio emission is inconsistent with the observations. The results are very sensitive to the value of M_{st} for a given $P_c(r)$. Basically, changing E_a and M_{st} correspond to changing E_{max} and x , respectively.

Figure 5 shows the surface brightness profiles for Model LCR0 at $t = 9 \text{ Gyr}$ with $M_{st} = 2.1$ and $E_a = 1 \times 10^{60} \text{ erg s}^{-1}$. The model generally reproduces the surface brightness profile observed in the radio band, although we did not intend to reproduce that when we calculated Model LCR0 in Paper I. In that figure, the surface brightness rapidly increases toward the cluster center for the synchrotron radio emissions because of the increase of the magnetic fields toward the cluster center ($B(r) \propto \rho(r)^{2/3}$). On the other hand, the profile for the IC emissions is relatively flat because electrons scatter CMB photons, which are uniformly distributed. The size of the region with high surface brightness is regulated by radiative cooling, because radiative cooling increases the ICM density and makes a cool core. On the other hand, CRs can fill the entire core with fast Alfvén waves (Paper I).

Proton-proton interactions are effective in such a high-density region. The surface brightness for thermal Bremsstrahlung slightly decreases at the cluster center, because the ICM temperature decreases there (Figure 1a).

We also study a less massive cluster. Figure 6 shows the spectra of the entire core ($r < 1$ Mpc) at $t = 9$ Gyr calculated using parameters of Model SCR0 in Paper I. For this model, we adopted the observed gravitational potential of the Virgo cluster. The efficiency of AGN energy input is $\epsilon = 1 \times 10^{-4}$. Although we recalculated the ICM and CR distributions, they are almost identical to those calculated in Paper I. The ICM temperature outside the core is ~ 2 keV. We take $M_{st} = 2.1$ ($x = 3.2$) and $E_a = 1 \times 10^{59}$ erg s $^{-1}$. The distance to the cluster is set to be 16 Mpc. We take $\omega = 0.7$, which is an good approximation for $r \lesssim 50$ kpc (Figure 11 in Paper I). The shock radius and age are $R_{st} = 21$ kpc and $t_{at} = 6.3 \times 10^6$ yr, respectively. The maximum energy of CRs is $E_{\max} = 3.3 \times 10^4$ TeV. The gamma-ray flux is much smaller than the upper limits for the Virgo cluster obtained with *Fermi* (Ackermann et al. 2010). The luminosity is sensitive to M_{st} but not to E_a . The surface brightness profiles for this model are shown in Figure 7. The surface brightness is smaller than that in Figure 5.

4. Discussion

We have studied the non-thermal spectra of cool cores heated by CR streaming. The results indicate that the Mach number of the shock that accelerate CRs must be small (~ 2) to be consistent with radio observations at least for the Perseus cluster. We think that this is reasonable because the temperature and the sound velocity of the ICM is large and thus it is difficult for the cocoon shock to have a large Mach number. The small Mach number means that the CR spectrum must be steep. In Paper I, we did not specify the injection mechanism of CRs. We emphasize that even if CRs are injected by anything other than the cocoon, the spectrum must be steep for the given P_c .

Recently, Enßlin et al. (2011) indicated that the CR streaming velocity may be much larger than the Alfvén velocity v_A in the hot ICM. This is because in high- β plasma, where β is the ratio of thermal to magnetic energy, waves may suffer strong resonant damping by thermal protons. In this case, the sound velocity c_s may be appropriate as the streaming velocity instead of v_A (Holman et al. 1979; Enßlin et al. 2011). Thus, we simply replace v_A by c_s in equations (4) and (5) and see what would happen. Figures 8 and 9 show the profiles of the ICM and CRs for the parameters of Model LCR0 except for the larger streaming velocity c_s ; we refer to this model as Model LCRs. The ICM is stably heated by the CR streaming even in this model and the evolution of \dot{M} is not much different from that in Model

LCR0. Compared with Figures 2, the fraction of CR pressure is small in the central region because of the larger streaming velocity and the escape of CRs. Since the ICM temperature is an increase function of radius (Figure 8), the sound velocity or the streaming velocity is also an increasing function. Thus, P_c/P_g tends to decrease outward fairly rapidly. Figures 10 and 11 are the same as Figures 3 and 5 but for Model LCRs. If we assume $M_{st} = 2.1$ as is the case of Model LCR0, non-thermal luminosities in Model LCRs are smaller than those in Model LCR0, because more CRs have escaped from the core with the high ICM density. Thus, we increase the Mach number and set it to be $M_{st} = 2.4$. We present the spectra and surface brightness in Figures 10 and 11. The synchrotron spectrum and the surface brightness are consistent with the observations.

Regardless of the streaming velocity, the CR spectra in the cores must be steep, because if not, the luminosities are too large (Figure 4b); this is inconsistent with the small number of clusters in which radio mini-halos have been observed (Govoni et al. 2009) and the non-detection of gamma-rays from clusters. Because of the steep spectra, future observations in the low-frequency radio band would be useful. Thus, cool cores would be promising targets for radio telescopes such as *LOFAR*. The number of mini-halos may increase as the sensitivities of radio telescopes are improved. In our model, we assumed that CRs are mostly accelerated when the Mach number of the shock is $M_s \sim M_{st}$. For real clusters, however, we expect that the Mach number M_s decreases and that the CR spectrum at the shock steepens during the expansion of a cocoon. Thus, we expect that the spectral index should increase outwards in the cluster, which has actually been observed in the radio band (Sijbring 1993; Gitti et al. 2002), although the interferometric nature of these measurements might result in smaller radio halos at higher frequencies (missing zero spacing problem). On the other hand, observations in other bands would be difficult in the near future (Figures 3 and 6). In the X-ray band, IC emissions should be observed (Figures 3 and 6). However, thermal emissions from cool cores are very bright, which makes it difficult for the non-thermal emission to be detected. For the Perseus cluster, Sanders, Fabian, & Dunn (2005) claimed the detection of non-thermal emission with a flux of 6.3×10^{-11} erg cm $^{-2}$ s $^{-1}$ between 2 and 10 keV. However, the detection was not confirmed by later observations (Molendi & Gastaldello 2009; Eckert & Paltani 2009). Even with hard X-ray telescopes that will be launched in the near future such as *NuSTAR* and *Astro-H*, the detection may be difficult because of the low surface brightness (Figures 5 and 7). For the detection in the gamma-ray band, good angular resolutions as well as sensitivities are required, because gamma-rays could also be emitted from the central AGNs (e.g. Abdo et al. 2009; Kataoka et al. 2010), which must be resolved.

The steep CR spectra mean that most of the CRs in cool cores have low energies. Thus, indirect studies may be useful. For example, optical filaments observed in cool cores may be heated by those CRs (see Ferland et al. 2009; Bayet et al. 2010). We note that the CR

heating is locally unstable, and that the filaments could be created through local thermal instabilities (Paper I). Moreover, our model does not require turbulence for stable heating. Thus, cool cores in which turbulence is not developing may be observed with detectors having high spectral resolutions such as *Astro-H*, while the detection of turbulence does not deny our model. Although we did not consider primary electrons, they may be accelerated at shocks in cores in spite of the low Mach numbers (Matsukiyo et al. 2011), and the emissions from them may be observed in some clusters.

Finally, we caution the reader that we did not consider energy-dependent diffusion of CRs, because we do not know the actual diffusion coefficient in the ICM, especially away from the shock front (see Fujita et al. 2011). If CRs with higher energies escape from the core faster than those with lower energies, the energy spectrum could be steep (e.g. Fujita et al. 2009; Ohira, Murase, & Yamazaki 2010, 2011). Moreover, we did not include the contribution of gamma-rays from CRs accelerated at cosmological shocks and those from dark-matters (e.g. Totani 2004; Pinzke & Pfrommer 2010; Pinzke, Pfrommer, & Bergstrom 2011).

5. Conclusions

We have investigated non-thermal emissions from cool cores heated by CRs. For the distributions of CRs, we used the model in which the cores are stably heated by CR streaming. CR protons interact with ICM protons and produce secondary electrons and π^0 -decay gamma-rays. We found that the CR spectra must be steep in order to be consistent with observations of a radio mini-halo. The steep spectra reflect the fact that the CRs are accelerated at shocks with low Mach numbers (~ 2) in hot ICM. We have also studied the dependence on the CR streaming velocity and found that the stronger shocks are required to be consistent with the observations for the larger CR streaming velocity. Since most of the CRs in cores have low energies, synchrotron emissions from them should be observed in low-frequency radio bands. Thus, the number of clusters that have radio mini-halos would increase as the sensitivities of radio telescopes increase. On the other hand, the detection in other bands such as the X-ray and gamma-ray bands would be difficult in the near future. The low-energy CRs could be studied by observing optical filaments that are often found in cool cores.

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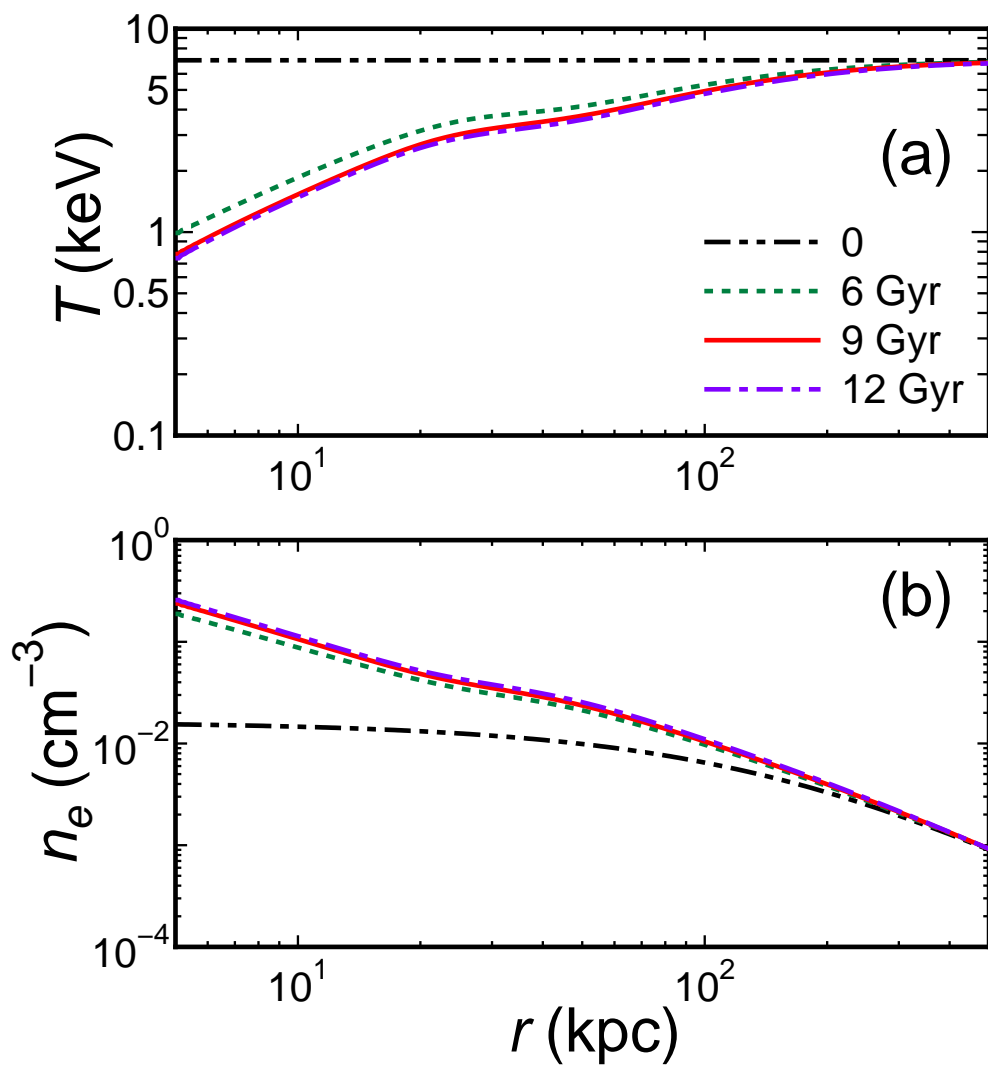


Fig. 1.— (a) Temperature and (b) density profiles for Model LCR0.

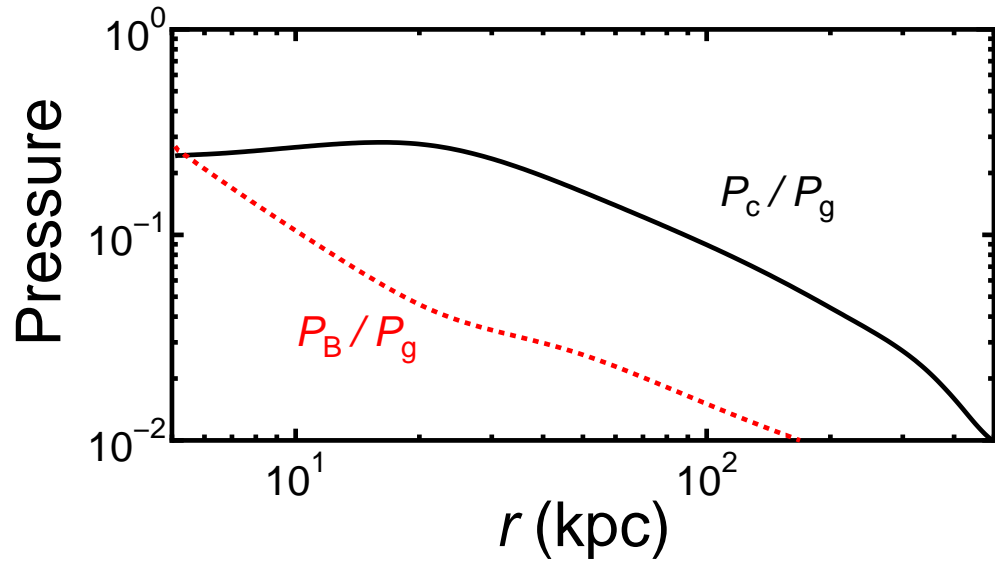


Fig. 2.— Profiles of the ratios P_c/P_g (solid) and P_B/P_g (dotted) at $t = 9$ Gyr for Model LCR0.

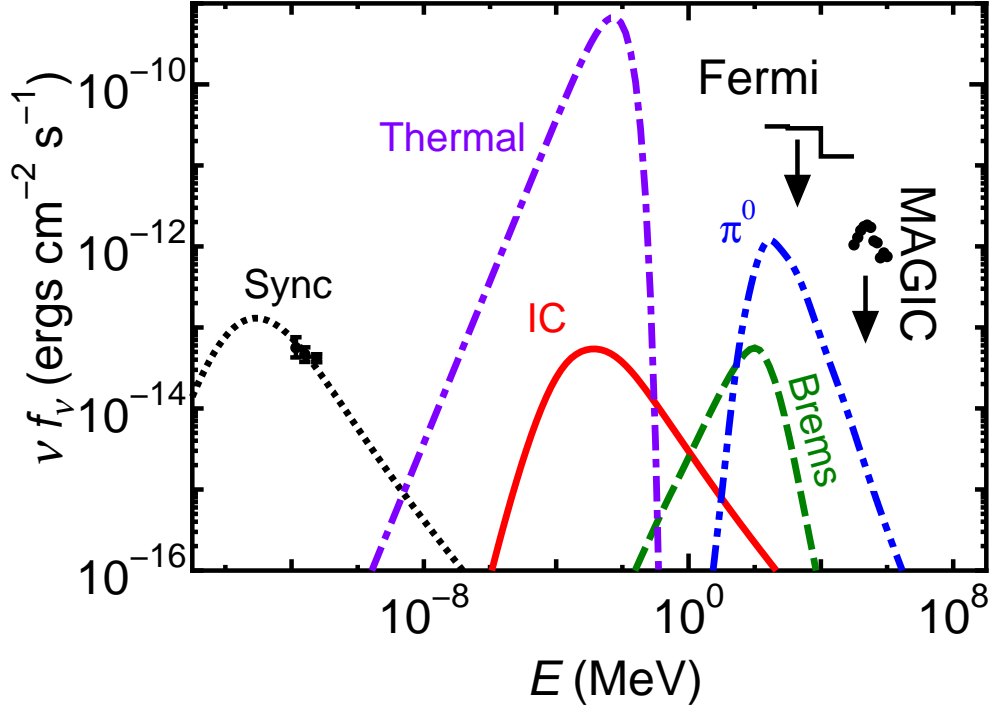


Fig. 3.— Spectra calculated based on Model LCR0 with $M_{st} = 2.1$ and $E_a = 1 \times 10^{60}$ erg s $^{-1}$. The synchrotron radiation (dotted line), IC scattering (solid line) and non-thermal bremsstrahlung (dashed line) are of the secondary electrons. The π^0 decay gamma-rays are shown by the two-dot-dashed line. The thermal bremsstrahlung is shown by the dot-dashed line. Observations are for the Perseus cluster. Radio observations are shown by dots (Sijbring 1993; Gitti et al. 2002), and gamma-ray upper limits are shown by arrows (Ackermann et al. 2010; Aleksić et al. 2010).

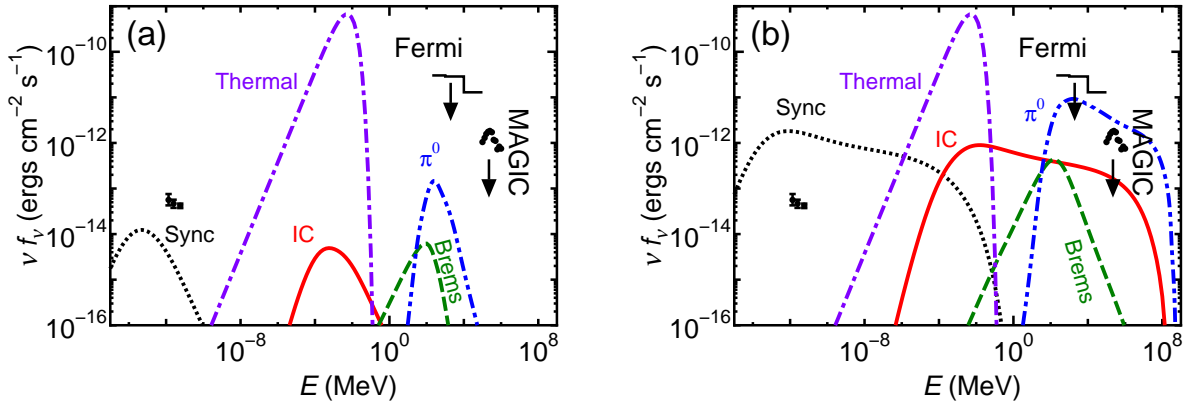


Fig. 4.— Same as Fig. 3 but for (a) $M_s = 1.8$ and (b) 4.0.

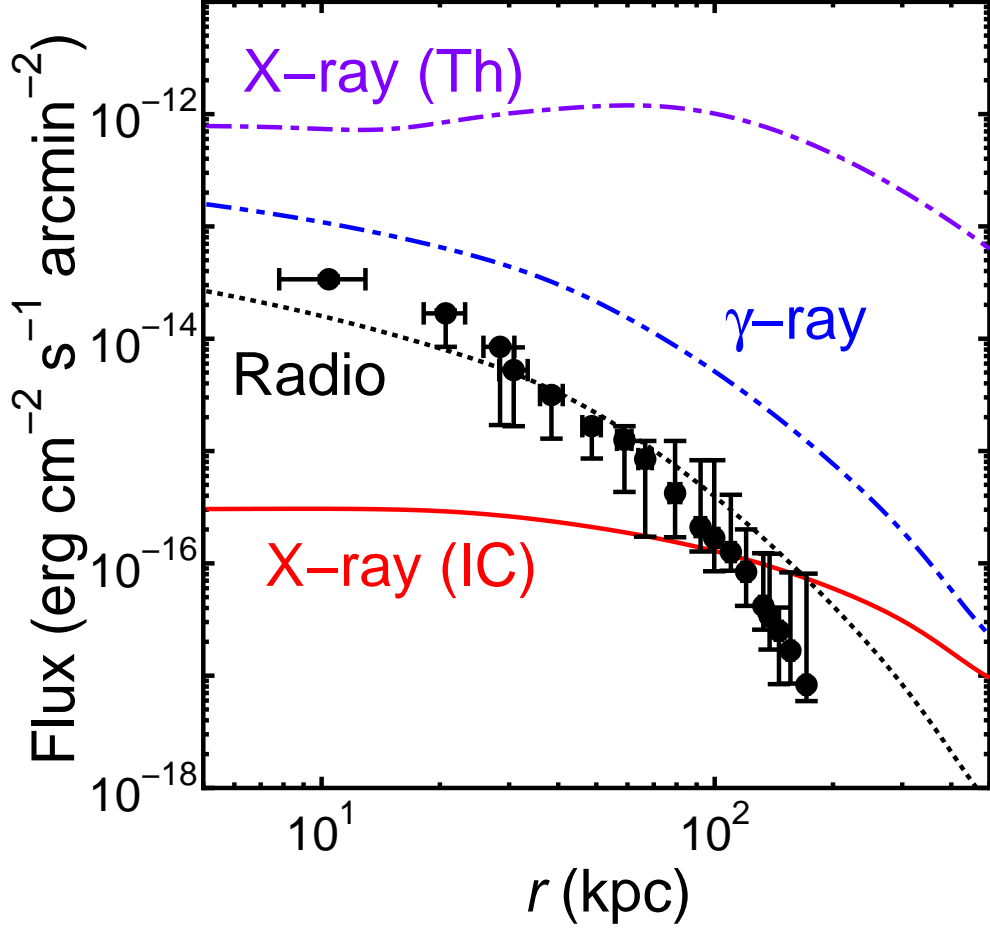


Fig. 5.— Surface brightness of non-thermal and thermal emissions calculated based on Model LCR0 with $M_{st} = 2.1$ and $E_a = 1 \times 10^{60} \text{ erg s}^{-1}$. The synchrotron radiation (327 MHz; dotted line), IC scattering (20 keV; solid line), π^0 decay gamma-rays (1 GeV; two-dot-dashed line), and thermal Bremsstrahlung (20 keV; dot-dashed line) are shown. Radio observations for the mini-halo in the Perseus cluster are shown by dots (Gitti, Brunetti, & Setti 2003). The vertical errors include the deviations from the spherical symmetry.

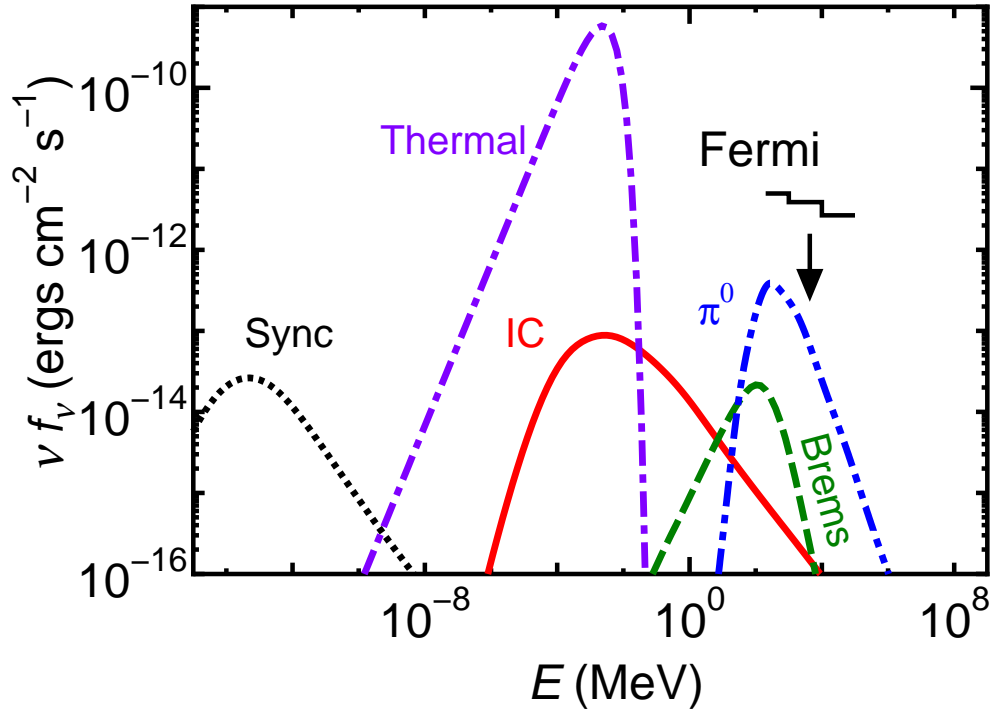


Fig. 6.— Same as Fig. 3 but for Model SCR0. Gamma-ray upper limits are shown by an arrow (Ackermann et al. 2010).

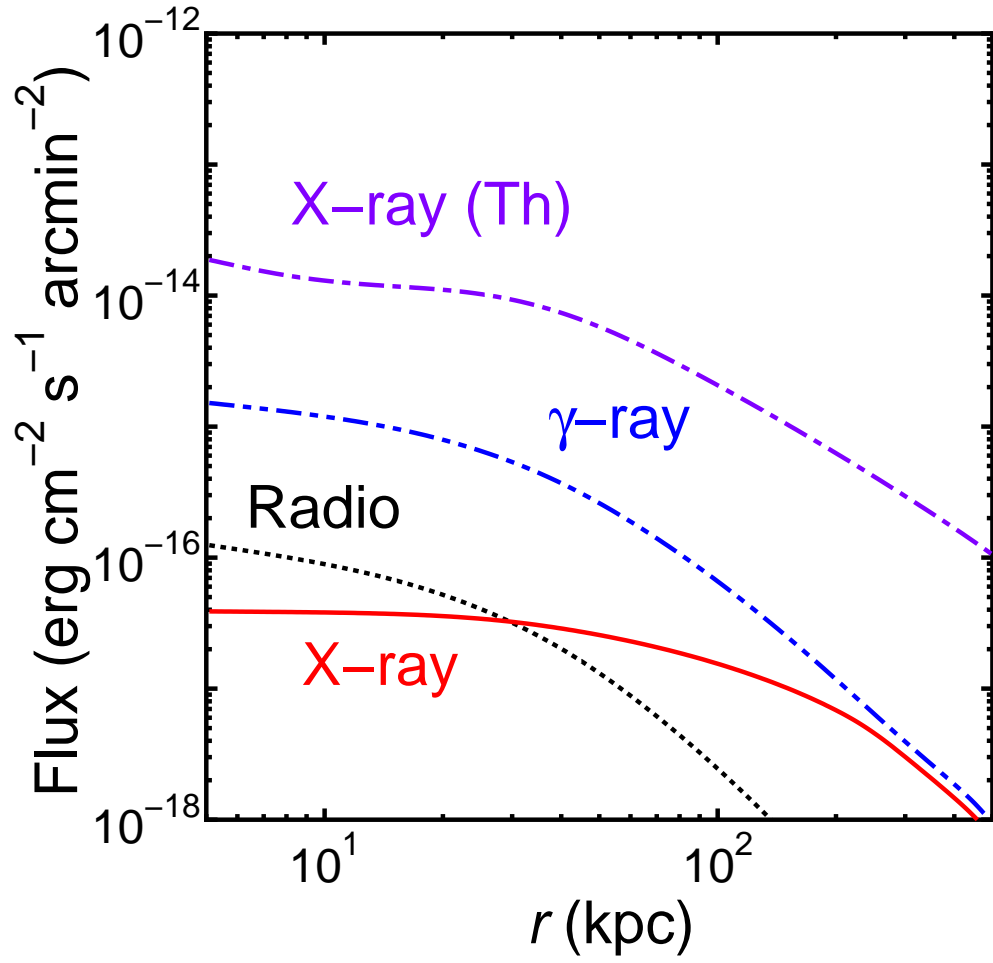


Fig. 7.— Same as Fig. 6 but for Model SCR0.

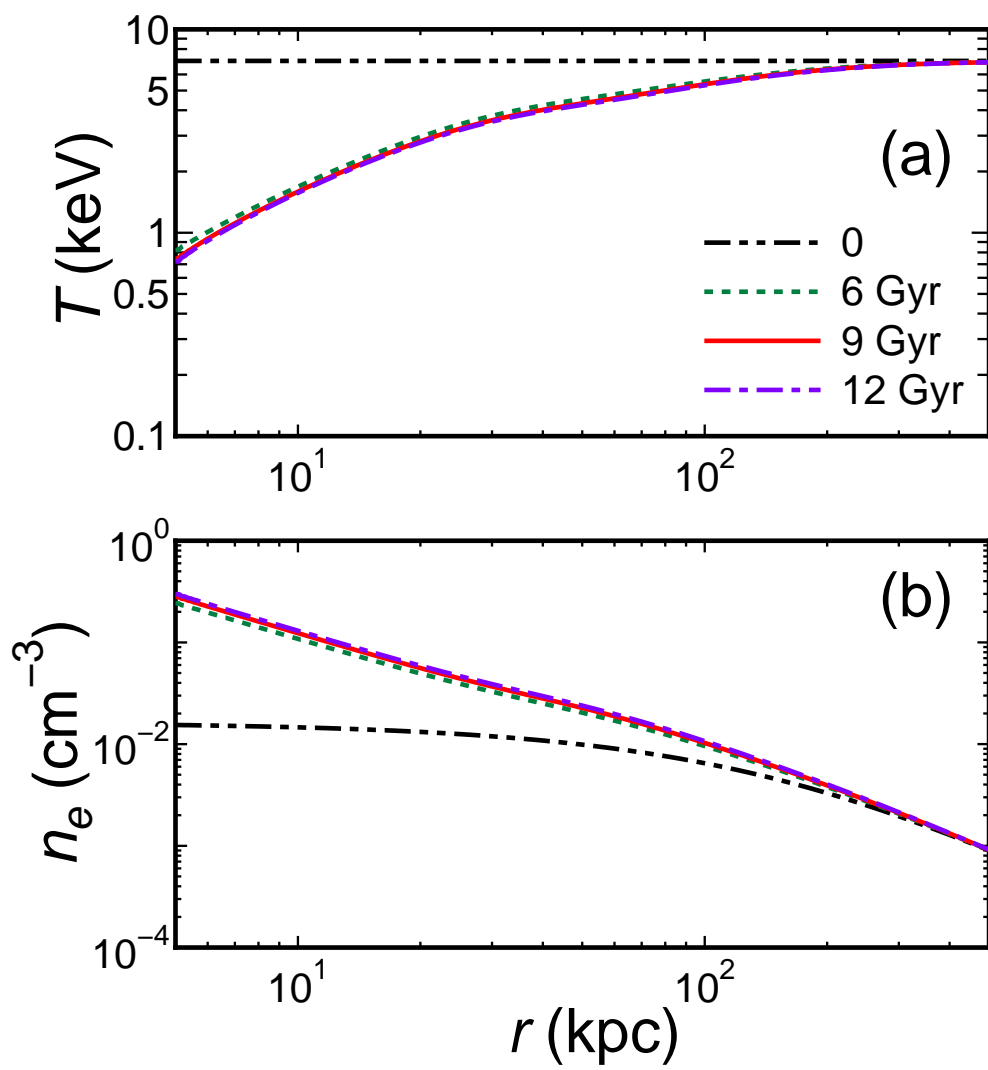


Fig. 8.— Same as Fig. 1 but for the Model LCRs.

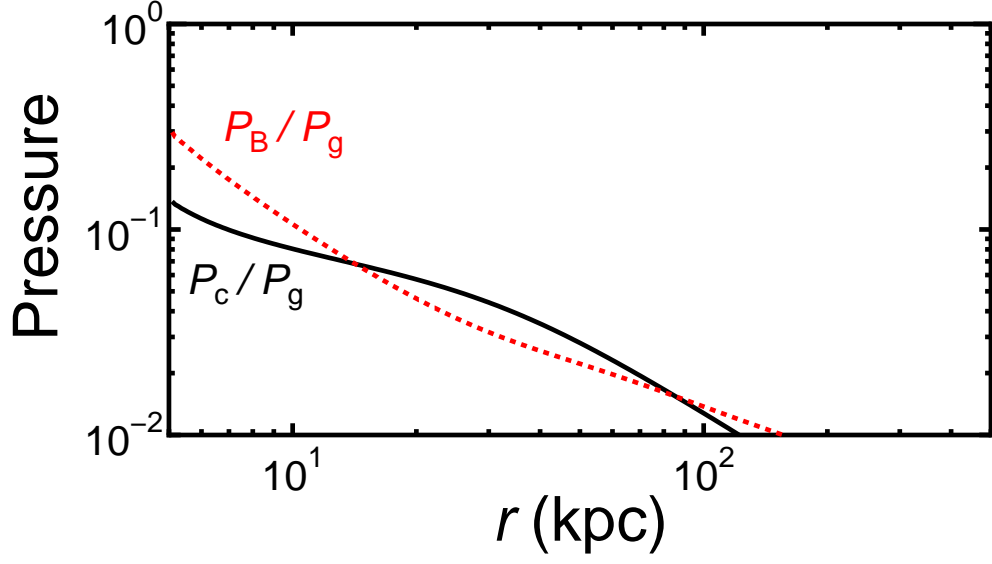


Fig. 9.— Same as Fig. 2 but for Model LCRs.

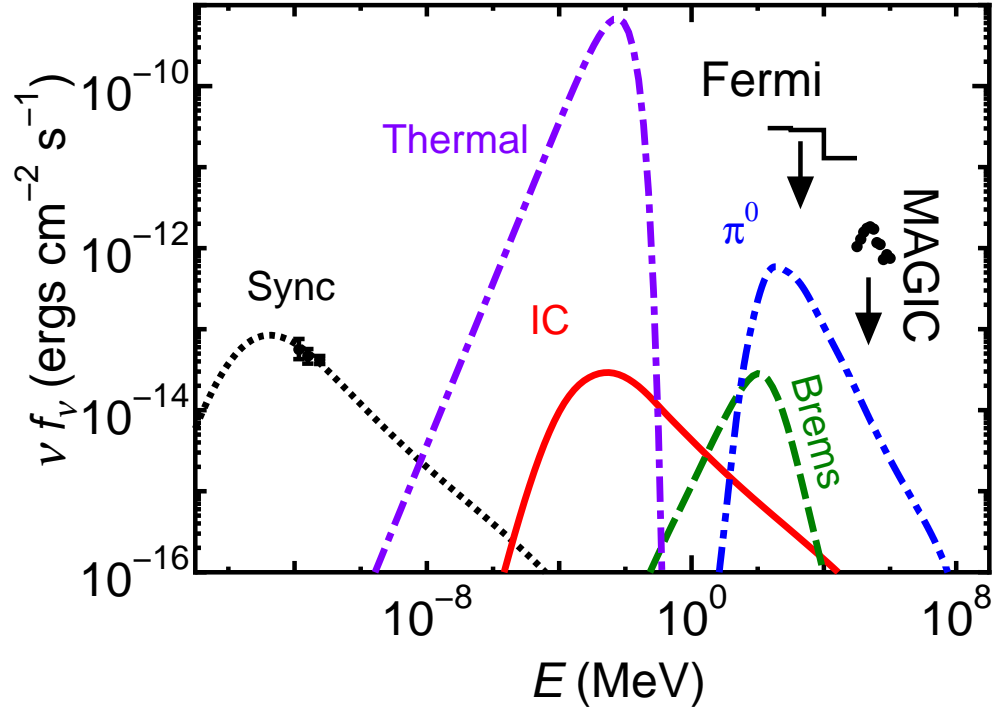


Fig. 10.— Same as Fig. 3 but for Model LCRs and $M_{st} = 2.4$.

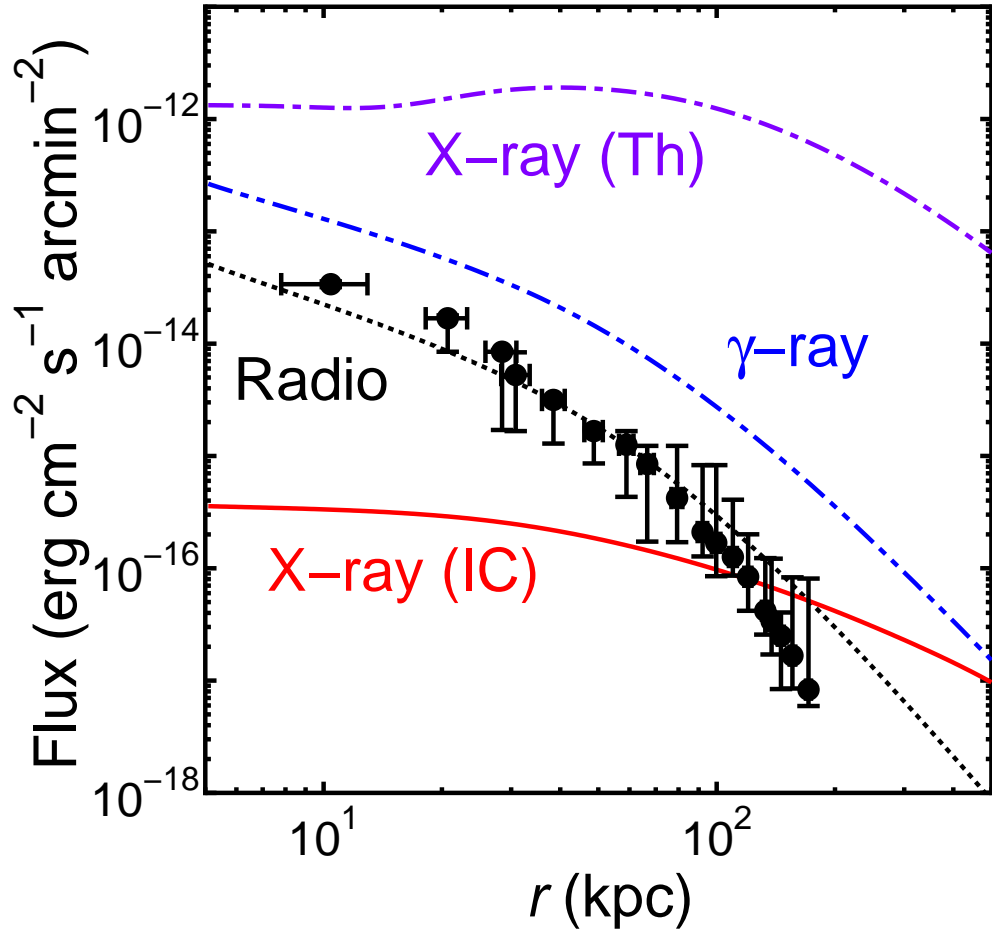


Fig. 11.— Same as Fig. 5 but for Model LCRs and $M_{st} = 2.4$.